GEOPHYSICAL SURVEYS FOR
GROUND WATER INVESTIGATIONS
CENTRAL OAHU
OAHU, HAWAII

GEOPHYSICAL SURVEYS FOR GROUND WATER INVESTIGATIONS CENTRAL OAHU OAHU, HAWAII

Prepared For:

Ewa Plain Water Development Corporation
828 Fort Street Mall, Suite 500
Honolulu, HI 96813

Prepared By:

Blackhawk Geosciences, Inc.
17301 West Colfax Avenue, Suite 170
Golden, CO 80401

(BGI Project #90034)

September 11, 1990

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EXECUTIVE SUMMARY

Time domain electromagnetic (TDEM) soundings were used to assist in the ground water evaluation of the Central Oahu area on the island of Oahu, Hawaii.

The results of the TDEM survey show:

(1) The unconformity between the Waianae and Koolau lava flows was detected and mapped on four TDEM survey lines from line 3N toward the south and not detected north of line 3N. Good agreement was observed about the presence, depth of occurrence, and thickness of the unconformity mapped in a borehole and interpreted from TDEM soundings. From TDEM measurements along lines on both sides of the unconformity no consistent influence of the unconformity on fresh water head could be observed.

(2) The elevation of the fresh-salt water interface was mapped throughout the survey area. Over most of the survey area the elevation of the salt water interface ranges from -600 ft to -900 ft below msl. This range is consistent with observations of fresh water head in wells, although locally some differences between TDEM interpretations and heads observed in wells occur. An important conclusion from the TDEM survey is that large fresh water resources exist uniformly throughout the survey area with heads above 15 ft.

1.0 INTRODUCTION

TDEM geophysical surveys were conducted during March and July, 1990, on the Island of Oahu, Hawaii by Blackhawk Geosciences, Inc. (BGI) for Ewa Plain Water Development Corporation (EPWDC). The surveys were performed to assist in the evaluation of the hydrogeologic section of the Central Oahu area. The objectives of this survey were:

(1) To establish the existence, or lack of the Waianae/Koolau unconformity, delineated in the previous survey of March 1990, and its influence on the ground water regime.

(2) To better define the elevation of the fresh-brackish/salt water interface on either side of the Waianae/Koolau unconformity.

The primary object of the geophysical survey was to determine the elevation and thickness of the lens of fresh water floating on salt water. Because the electrical resistivity of rock formations is highly dependent upon the salinity of ground water, an electrical surface geophysical technique was chosen to map the elevation of salt water. A secondary objective of the survey was to detect the existence or lack of the unconformity, which is expected to exhibit a resistivity contrast from surrounding rock types.

Previous geophysical surveys by Kauahikaua and Jackson (1988) near Kunia, on the island of Oahu using Schlumberger soundings, show a conductive layer to be successfully traced eastward from the Waianae mountains that is interpreted to correspond to an unconformity between Waianae and Koolau lava flows.

The specific electromagnetic technique selected was the TDEM method because of its better lateral and vertical resolution, compared to other electrical and electromagnetic techniques.

2.0 LOGISTICS AND DATA ACQUISITION

2.1 GENERAL

The TDEM survey was accomplished by a three man crew consisting of two BGI personnel and one local temporary field helper. The location of the geophysical survey lines were determined from the results of the prior March 1990 survey and from consultation with EPWDC personnel and their consultants. During the March 1990 survey, the majority of TDEM soundings were acquired along two east-west lines. The prior measurements along line 1N, near the 400 ft elevation (Fig. 2-1), were able to map the Waianae/Koolau unconformity into the saline water interface, but not on line 2N. Therefore, additional soundings along five roughly east-west lines were acquired to help define the unconformity and map the fresh-salt water interface. The survey lines and loop locations of the TDEM soundings for both surveys (March and July 1990) are shown on Figure 2-1. The results of the March 1990 survey are contained in a report delivered to EPWDC in April 1990, and they are also incorporated into this report.

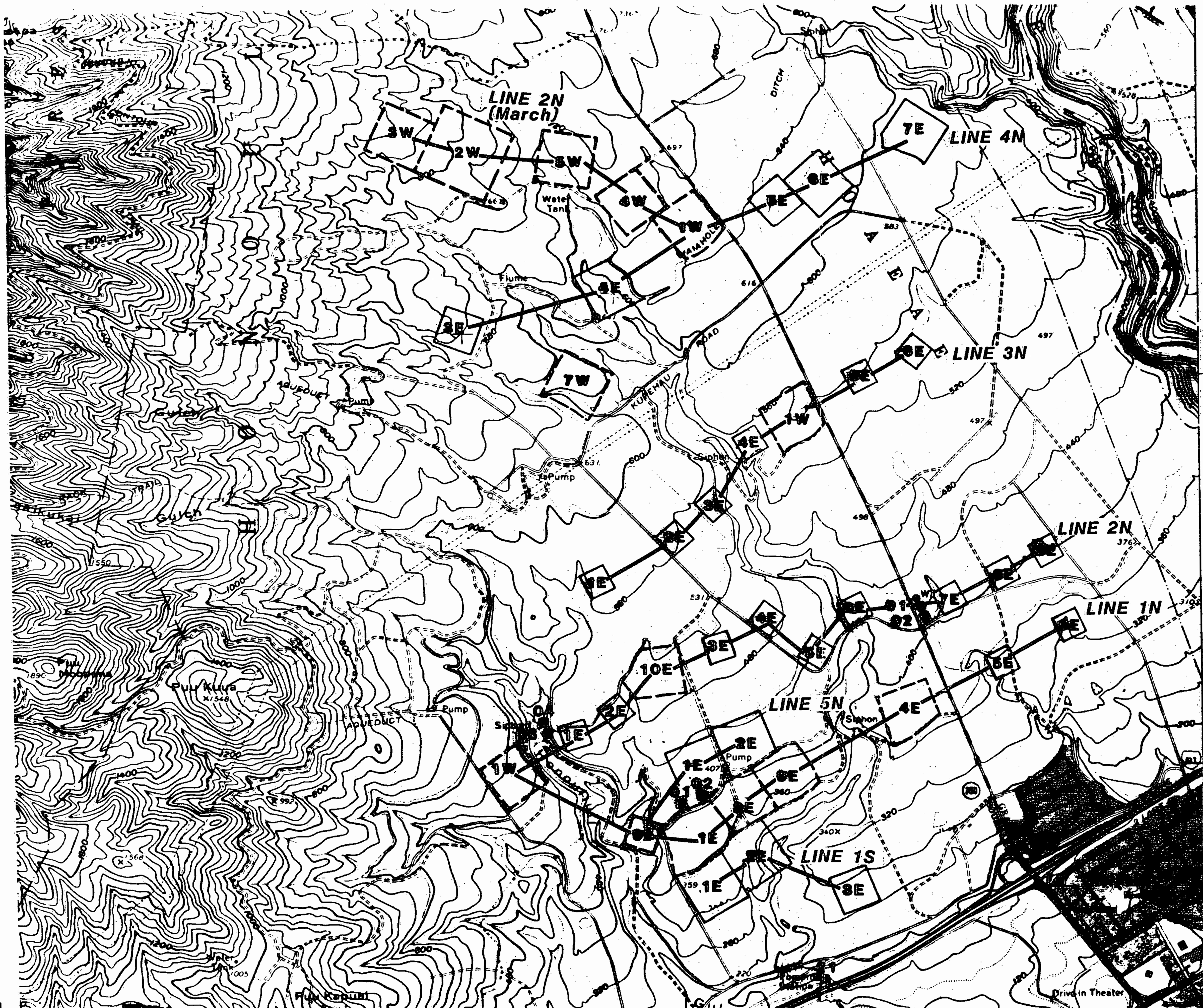
During the nine and one-half days of field work in July 1990, a total of 27 soundings were acquired over the Central Oahu area. A daily log of field activities during this survey is given in Table 2-1. Sounding locations were surveyed using a compass and hip-chain from known road junctions located on the field map. Elevations of sounding centers were obtained from the USGS map and measured with an altimeter in the field.

Loop sizes varied according to coverage needed on survey lines and available road access. Throughout the survey area, often two measurements were made at each location to resolve both the shallow thin unconformity, as well as the deeper saline water interface. This was accomplished by using large (up to 1,500 ft by 1,500 ft) transmitter loops for deeper exploration, and smaller (400 ft to 600 ft) for shallower exploration depth.

From the start of the survey a work restriction was placed upon the field crew by the landowner. The restriction was that during the work week (Monday through Friday), the TDEM crew could only energize the transmitter loops after 3:30 p.m. when sugar cane employees had completed their work day. This restriction inhibited productivity during the work week.

2.2 PROCEDURES

The Geonics EM-37 TDEM system was utilized on this survey. The system basically consists of a transmitter and a receiver. The transmitter loop is constructed of 10 to 12 gauge insulated copper wire. The wire is laid on the ground surface in a square loop varying in size, depending upon the required depth of investigation (larger loop sizes for deeper measurement). A transmitter and motor generator are connected into the loop at one corner. A time-varying current is pulsed through the wire at two different base frequencies. The TDEM receiver measures and records the decay of the vertical magnetic field through a receiver coil placed at the center of the non-grounded transmitter loop. Receiver coils with effective areas of 100 m^2 and 1,000 m^2 were utilized at base frequencies of 3 Hz and 30 Hz. During data acquisition numerous transient decays are collected with the receiver for each sounding. Readings were acquired at several receiver gains with opposite receiver polarities for each sounding location. The readings were stored in a DAS-54 solid state data logger, and were nightly transferred to a personal computer for processing. A technical note is given in Appendix A which describes and illustrates the principles of TDEM.



LEGEND

Geoelectric Cross Section

1W Sounding Loop Location

1W March 1990 Survey

01 Well Locations and Number (2303-01)

OAHU

HAWAIIAN ISLANDS

QUADRANGLE LOCATION

Schofield Barracks USGS Quad.

2000 0 2000

SCALE - FEET

BLACKHAWK GEOSCIENCES, INC.

GEOPHYSICAL SURVEY LOCATION MAP

Ewa Plains Water Dev. Corp.

Central Oahu, Hi.

PROJECT NO: 90034

FIGURE 2-1

Table 2-1. Daily log of field activities

Date (1990)	Activity
July 11	Mobilization from Denver, CO to Honolulu, HI.
July 12	Meet with personnel from Campbell Estates and Oahu Sugar.
July 14	Central Oahu soundings 2N1E, 2N2E and 2N3E.
July 15	Central Oahu soundings 2N4E, 2N5E and 2N6E.
July 17	Central Oahu soundings 2N7E, 2N8E and 2N9E.
July 18	Central Oahu soundings 3N1E, 3N2E and 3N3E.
July 19	Central Oahu soundings 3N4E, 3N5E and 3N6E.
July 20	Central Oahu soundings 4N5E, 4N6E and 4N7E.
July 21	Central Oahu soundings 5N1E and 5N2E.
July 22	Central Oahu soundings 1S1E, 1S2E and 1S3E.
July 23	Central Oahu soundings 4N3E and 4N4E.
July 24	Central Oahu soundings 1N5E and 1N6E (1/2 day).
July 25	Demobilize equipment and BGI personnel.

Note: July 12, 13, 16 and 24 was work on other projects on Oahu.

3.0 DATA PROCESSING

The field data acquired each day was transferred from the DAS-54 data logger to a personal computer. The data for each sounding location is edited and combined (both 3Hz and 30 Hz frequencies) to produce a transient decay curve. This decay curve is transformed into an apparent resistivity curve, which is entered into an Automatic Ridge Regression Transient Inversion Program (ARRTI). From the apparent resistivity curve a one-dimensional model of resistivities and thicknesses is calculated.

The inversion program requires an initial estimate of the geoelectric section, including the number of layers, and the resistivities and thicknesses of each of the layers. The program then adjusts these parameters so that the model curve converges to best fit the curve formed by the field data set. The inversion program does not change the total number of layers within the model, but allows all other parameters to float freely.

In general, field data quality throughout the survey site was good, although several soundings (2N1W, 2N7W and 3N1W) near major power lines were effected by excessive 60-cycle noise.

The apparent resistivity curves and data sheets for all soundings for both data sets March and July 1990, are contained in Attachment A.

4.0 INTERPRETATION RESULTS

4.1 GENERAL

The results of the interpretations of individual soundings is the resistivity layering as a function of depth. Where soundings are acquired relatively close together the results of individual soundings can be plotted to form a geoelectric cross-section along a line. From the soundings acquired in July, a total of five geoelectric cross-sections were constructed. The two cross sections produced from the March 1990 data set are also included with this report, with two additional soundings added to line 1N. TDEM sounding locations and geoelectric section locations are shown in Figure 2-1.

To infer from the geoelectric cross-sections geologic and geohydrologic information, characteristic ranges of resistivities are assigned to known local geologic and geohydrologic units. The assigned resistivity ranges for the various units expected in the survey area are shown in Figure 4-1. An overlap occurs between the resistivity ranges. The most extensive overlap occurs between the clay soils or weathered volcanics and the dry unweathered or fresh-brackish water saturated volcanics. Since thick clay soils or weathered volcanics occur mainly at the surface, these two units can often be separated by their depth of occurrence in the section. The resistivity of the layer at the unconformity between Waianae and Koolau lava flows appears to fall in the same range as the clay soils and weathered volcanics. Throughout the survey area, zones of lower resistivity were detected below the unconformity in many of the TDEM soundings. These zones of lower resistivity could be caused by a combination of several factors which effect the resistivity of the hydrogeologic section. These factors are changes in lithology, porosity and salinity which influence formation resistivity.

In general, it is difficult to distinguish between fresh water saturated volcanics and brackish water (< 500 ppm chlorides) saturated volcanics by resistivity interpretation.

In the Central Oahu area survey the lower boundary of the fresh - brackish water lens was usually interpreted to be terminated by a conductive basal salt water layer. From the interpreted elevation of the salt water interface the amount of fresh water head above sea level and the thickness of the fresh - brackish water lens can be calculated using the Ghyben-Herzberg principle. This principle states that under conditions of static equilibrium, for every foot of fresh water above sea level there will be about forty feet of fresh water below sea level. An illustration of the Ghyben-Herzberg principle is given in Figure 4-2. All geoelectric sections show the elevation of the basal conductive layer in parentheses. Static heads can subsequently be calculated from these values using the Ghyben-Herzberg relation.

4.2 GEOELECTRIC CROSS-SECTIONS

Line 1 North (March and July data)

The geoelectric section for Line 1N is shown in Figure 4-3. In the geoelectric section the unconformity between the Waianae and Koolau lava flows was detected in soundings 1N9E, 1N1E, 1N2E and 1N3E. From the geoelectric section an apparent dip for the unconformity of approximately 10° towards the east is derived. At sounding 1N1W the uppermost layer is also interpreted as the unconformity, rather than surficial soils, because it is thicker than would be expected for soils, and it correlates with the apparent dip of the unconformity derived from soundings east of Honouliuli Gulch. At sounding 1N4E the conductive layer at -515 ft elevation is undetermined, i.e., it can be interpreted as a continuation of the unconformity or salt water saturated volcanics. The nature of the conductive layer at an elevation of -800 ft in sounding 1N5E is also undetermined, because its resistivity value of 14.3 ohm-m is higher than what would be expected for salt water saturated volcanics. At sounding 1N6E the conductive layer (25 ohm-m) above the salt water interface is interpreted to be weathered volcanics or a zone of increased salinity.

The elevation of the interpreted salt water saturated volcanics varies between -515 ft at 1N4E to about -800 ft at 1N5E, and averages approximately -650 ft. The elevation of the basal conductive layer is shown in parenthesis.

Wells in Honouliuli Gulch and near soundings 1N1E and 1N2E (Fig. 2-1) encountered water at static heads of 17 ft (personal communication with Tom Nance, 04/90). The head calculated for soundings in the vicinity of these wells using the Ghyben-Herzberg relation range from 14.7 ft to 19.8 ft. This difference between heads calculated from TDEM soundings and that measured in the boreholes is within interpretational error limits.

A comparison of the TDEM sounding results from sounding 1N1E and the geologic log from well 2303-01 is given in Figure 4-4. The results of the TDEM soundings are given in two formats on the left, (i) as a depth-resistivity log, and (ii) in terms of geohydrologic units using the classification shown on Figure 4-1. On the right side of the figure the condensed geologic log from well 2303-01 is shown. Good correlation between the TDEM interpretation and major geologic units is observed. The unconformity from the geologic log is found between -379 and

-485 ft in depth. In the TDEM interpretation the unconformity and zone of increased weathering above the unconformity have been interpreted as one conductive layer with a resistivity of 20 ohm-m and a thickness of about 225 ft.

Line 2 North (March 1990 data)

The results of the geoelectric cross-section for Line 2N (March 1990) are shown in Figure 4-5. The sounding locations are shown in Figure 2-1 (north of the Waiahole ditch). All soundings show a thick upper (≈ 125 ft to > 300 ft) conductive zone interpreted as soils and/or weathered volcanics. Along this section the layer at the unconformity between the Waianae and Koolau lava flows was not detected, except possibly at 2N1W. The resistivity ranges of the clay soils, weathered volcanics, and the unconformity are similar at 2N3W and 2N2W (Fig. 4-1). Therefore, the surficial conductive layer can either be soils and weathered rocks or the unconformity. The soundings show the fresh-saline interface to be deeper on the west side of the section with a distinct rise towards the eastern side. Sounding 2N1W shows a conductive layer (15 ohm-m) at a depth of approximately 520 ft (about 150 ft above sea level). This layer is interpreted as a zone of weathered volcanics or possibly a layer at the unconformity. This sounding was taken near the Kunia Road where several power lines are located which may have deteriorated data quality.

Line 2 North (July 1990 data)

Eleven soundings are incorporated in the data set for the geoelectric section of line 2N. The results are shown in Figure 4-6. In the geoelectric section the unconformity was detected in soundings 2N1E, 2N2E, 1N10E and 2N3E. At sounding 1N1W the upper conductive layer is interpreted as the unconformity because it correlates with the extension of the unconformity derived from soundings east of Honouliuli Gulch. At soundings 2N4E and 2N5E the presence of the unconformity is questionable, because of the inability in the interpretation to distinguish a thin conductive layer at depth near the salt water interface. The area below the unconformity with low resistivities (26 to 11 ohm-m) at soundings 2N3E and 2N4E is interpreted to be a zone of increased salinities. The elevation of the interface of the salt water saturated volcanics varies from -615 ft at 2N2E to about -910 ft at 2N8E, and averages about -750 ft.

The geologic log for Honouliuli Gulch Well 2303-03 shows the unconformity to be at elevations from approximately -80 ft to about -160 ft (Fig. 4-6). Static water heads of 17 ft were measured at the Honouliuli gulch wells and 22 to 25 ft at the Kunia II well locations (personal communication with Tom Nance, 06/90). The head calculated for soundings in the Honouliuli Gulch vicinity using the Ghyben-Herzberg relation range from

17.8 ft to 19.2 ft. The calculated head of soundings near the Kunia II wells vary from 17.8 ft to 19.7 ft. These calculations show good agreement at the wells near Honouliuli Gulch but not at the Kunia II area.

Line 3 North (July 1990 data)

The results of the geoelectric cross-section for line 3N are shown in Figure 4-7. All soundings exhibit an upper conductive layer (2 to 22 ohm-m) interpreted as clay soils and/or weathered volcanics. At soundings 3N1E and 3N2E a thin conductive (21 to 36 ohm-m) layer was detected below sea level along trend and with similar dip as the expected unconformity. This conductive zone is interpreted to be the extension to the north of the unconformity between the Waianae and Koolau lava flows. At soundings 3N3E and 3N4E the presence of the unconformity is questionable because of the inability in the interpretation to distinguish a thin conductive layer at depth near the salt water interface. At sounding 3N5E the conductive layer (22 ohm-m) at an elevation of -220 ft is interpreted as a layer of weathered volcanics and/or zone of increased salinity. The conductive basement layer at 3N5E could be interpreted as either a continuation of the unconformity or salt water saturated volcanics. At all soundings except 3N5E the elevation of the interface of salt water saturated volcanics is fairly consistent, between -812 ft to -936 ft.

Line 4 North (July 1990 data)

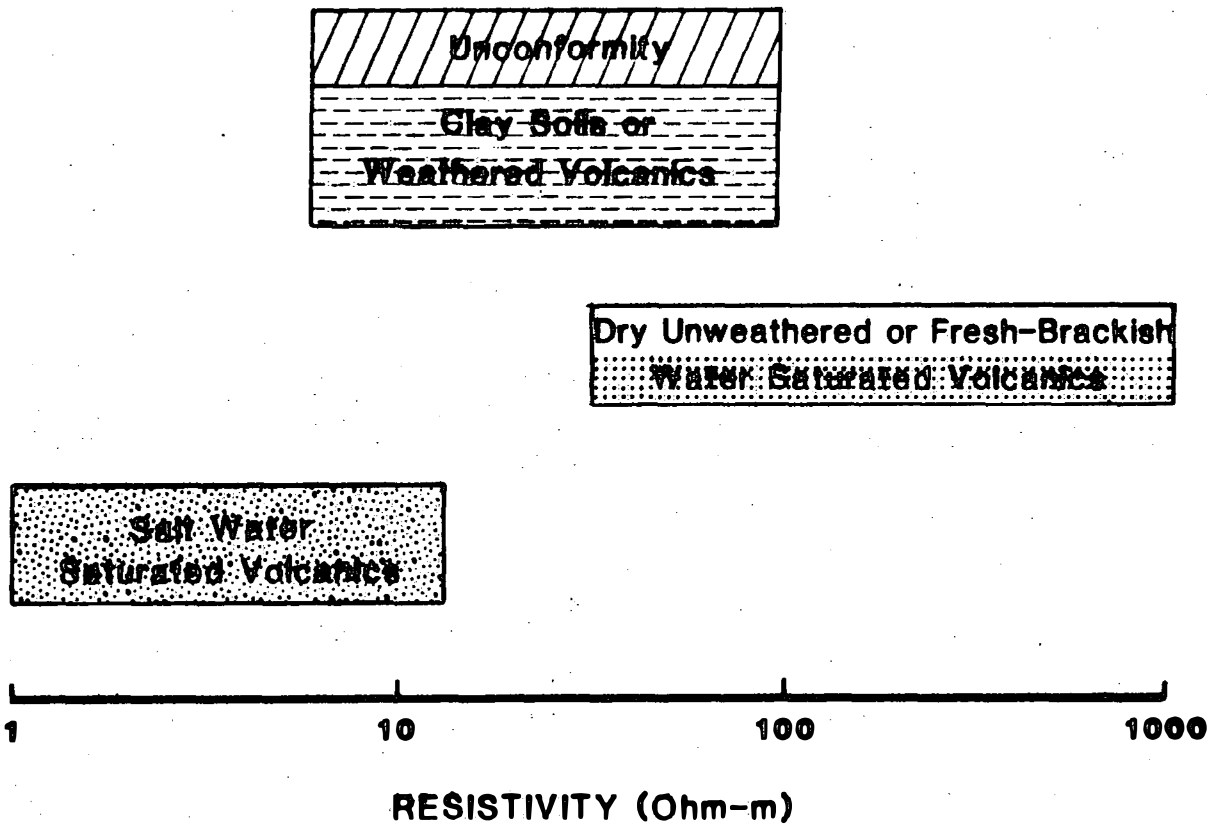
Five TDEM soundings were acquired along this survey line. The geoelectric cross-section for line 4N is shown in Figure 4-8. The results of this section show an upper relatively conductive layer (21 to 35 ohm-m) interpreted as clay soils and/or weathered volcanics. Along this section the layer at the unconformity between the Waianae and Koolau lava flows was not detected. The soundings show the fresh-brackish/salt water interface to be deeper on the east side of the section, at elevations of -878 ft and -1131 ft at soundings 4N6E and 4N7E, respectively. Sounding 2N1W (March) was left out of the section because of being distorted by power lines near Kunia Road.

Line 5 North (July 1990 data)

The geoelectric section for line 5N is shown in Figure 4-9. The two TDEM soundings were positioned just north of the upper Honouliuli Wells near the 400 ft elevation level. Sounding 1N9E was included in this section to help define the relative position and lateral extent of the unconformity layer. In the section, all soundings exhibit an upper conductive (28 to 36 ohm-m) layer interpreted as clay soils and/or weathered volcanics. The elevations of the fresh-brackish/salt water interface varies from -790 at 1N9E to -603 ft at 5N1E. The low resistivity of the volcanics below the unconformity at 5N2E is probably due to increased salinity in the basal water.

Line 1 South (July 1990 data)

Three TDEM soundings were acquired for this geoelectric cross-section south of line 1N. The results of the section are shown in Figure 4-10. The section shows the unconformity to be detected in sounding 1S1E and it is inferred in 1S2E and 1S3E. The lower boundary of the unconformity is questionable at soundings 1S2E and 1S3E, because of the inability in the interpretation to distinguish a thin conductive layer at depth near the salt water interface. The elevation of the fresh-brackish/salt water interface varies between -523 ft at 1S1E to -776 ft at 1S3E. The section shows the unconformity to intersect sea level at or west of 1S1E. This is a deviation from the general trend noticed in other cross sections to the north.



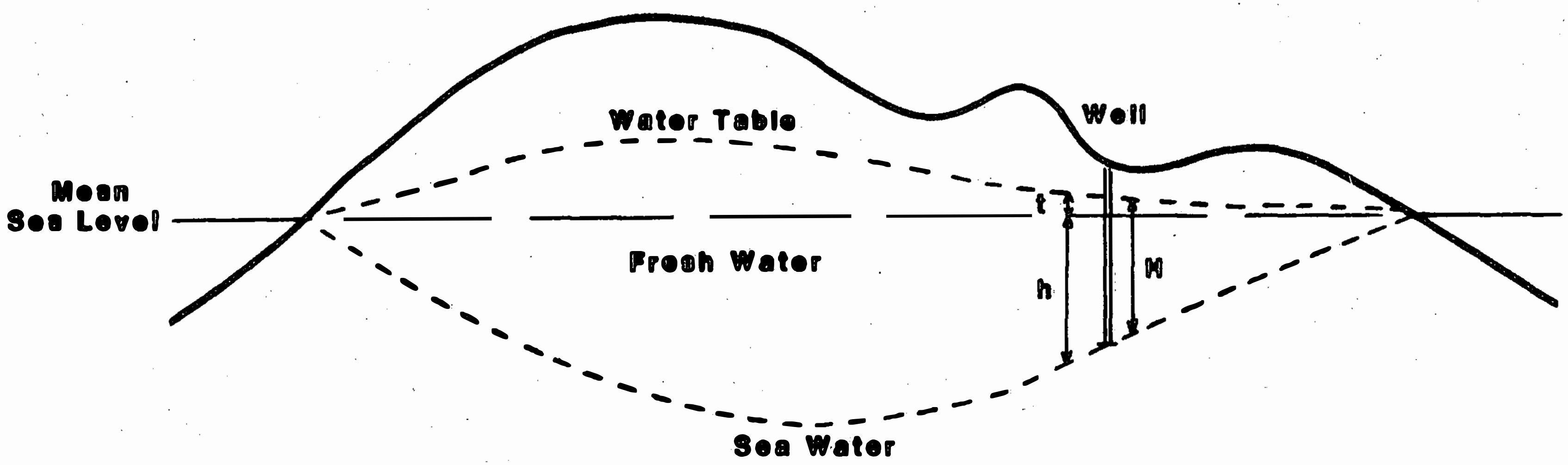
BLACKHAWK GEOSCIENCES, INC.

CHARACTERISTIC
RESISTIVITY RANGES

Ewa Plains Water Dev. Corp.
Central Oahu, Hi.

PROJECT NO: 90034

Figure 4-1



t = 1/40 (h)

FROM: HERZBERG

BLACKHAWK GEOSCIENCES, INC.

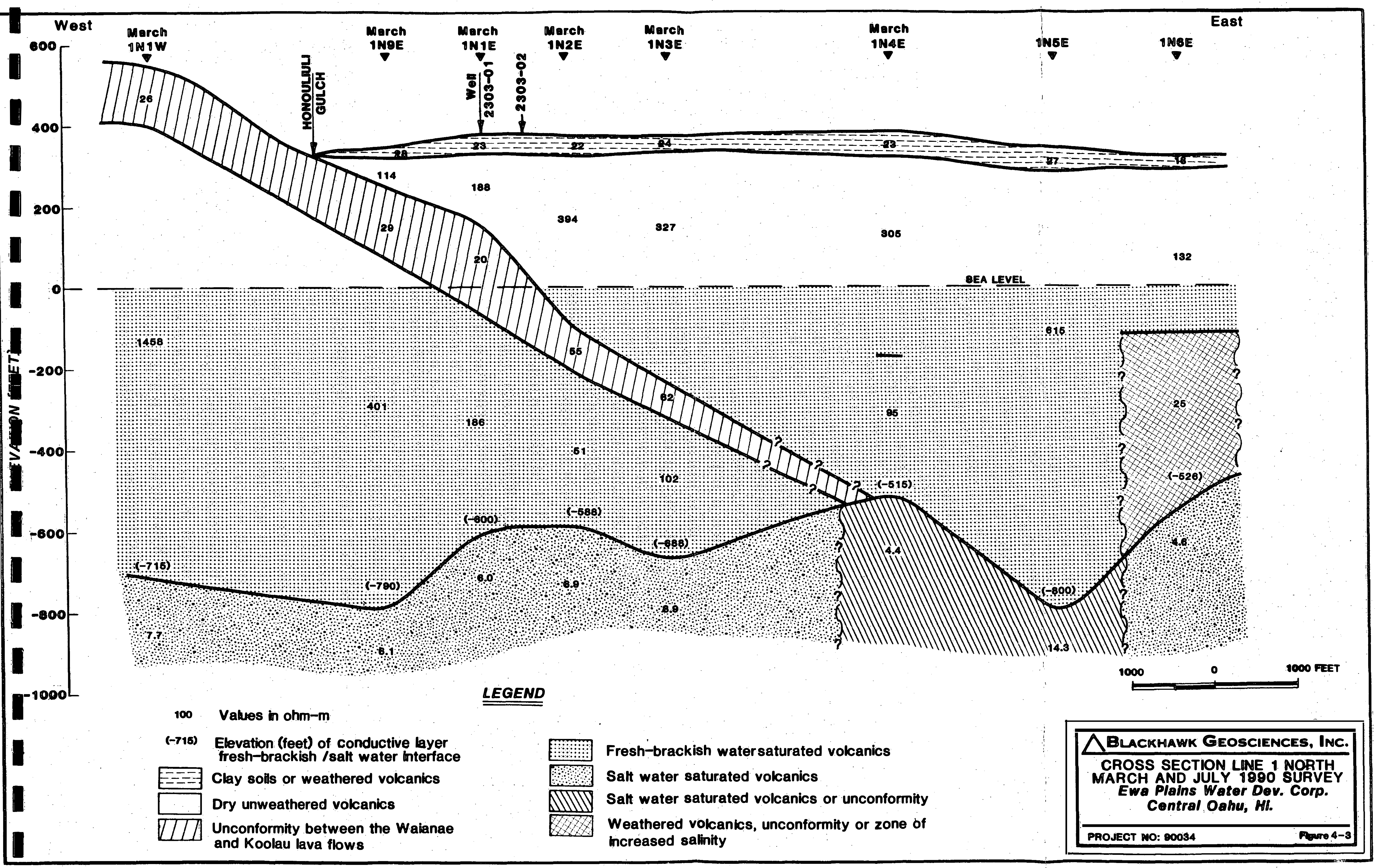
Illustration of the

Ghyben-Herzberg Principle

Ewa Plains Water Dev. Corp.

PROJECT NO: 90034

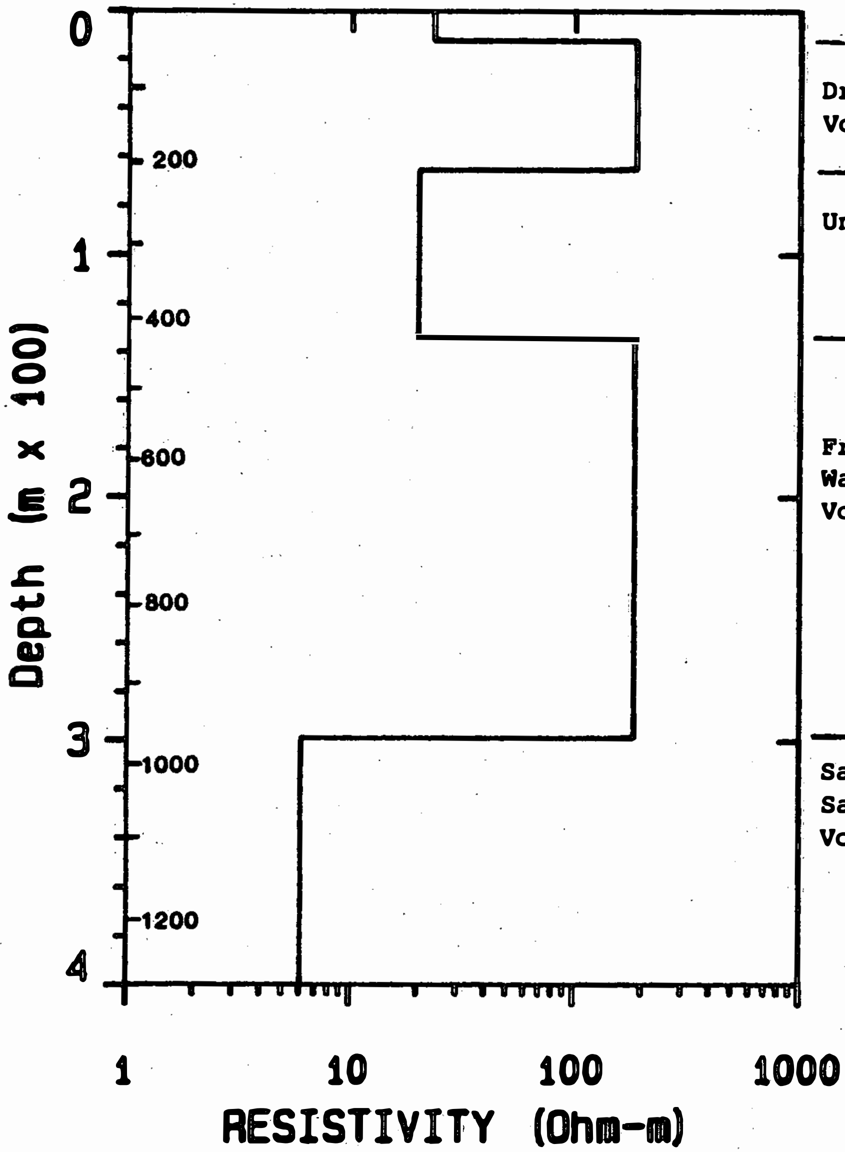
Figure 4-2



West
East
March 1N1W
March 1N9E
March 1N1E
March 1N2E
March 1N3E
March 1N4E
1N5E
1N6E
HONOULIULI GULCH
Well 2303-01
2303-02
SEA LEVEL
ELEVATION (FEET)
600
400
200
0
-200
-400
-600
-800
-1000
26
28
23
22
24
23
27
18
114
188
394
327
305
132
29
20
1458
615
55
62
95
25
401
186
51
102
(-515)
(-526)
(-600)
(-588)
(-686)
(-716)
(-790)
(-800)
4.4
4.6
6.0
6.9
8.9
7.7
6.1
14.3
1000
0
1000 FEET
LEGEND
100 Values in ohm-m
(-715) Elevation (feet) of conductive layer fresh-brackish /salt water interface
Clay soils or weathered volcanics
Dry unweathered volcanics
Unconformity between the Waianae and Koolau lava flows
Fresh-brackish water saturated volcanics
Salt water saturated volcanics
Salt water saturated volcanics or unconformity
Weathered volcanics, unconformity or zone of increased salinity
BLACKHAWK GEOSCIENCES, INC.
CROSS SECTION LINE 1 NORTH
MARCH AND JULY 1990 SURVEY
Ewa Plains Water Dev. Corp.
Central Oahu, HI.
PROJECT NO: 90034
Figure 4-3

TDEM Sounding Results 1N1E
(elv. 380 feet)

Depth (ft)	Geoelectric Interpretation (computed static head = 15 ft)	Hydrologic Interpretation
		Soil
		Dry Unweathered Volcanics
		Unconformity
		Fresh-Brackish Water Saturated Volcanics
		Salt Water Saturated Volcanics



Drilling Results

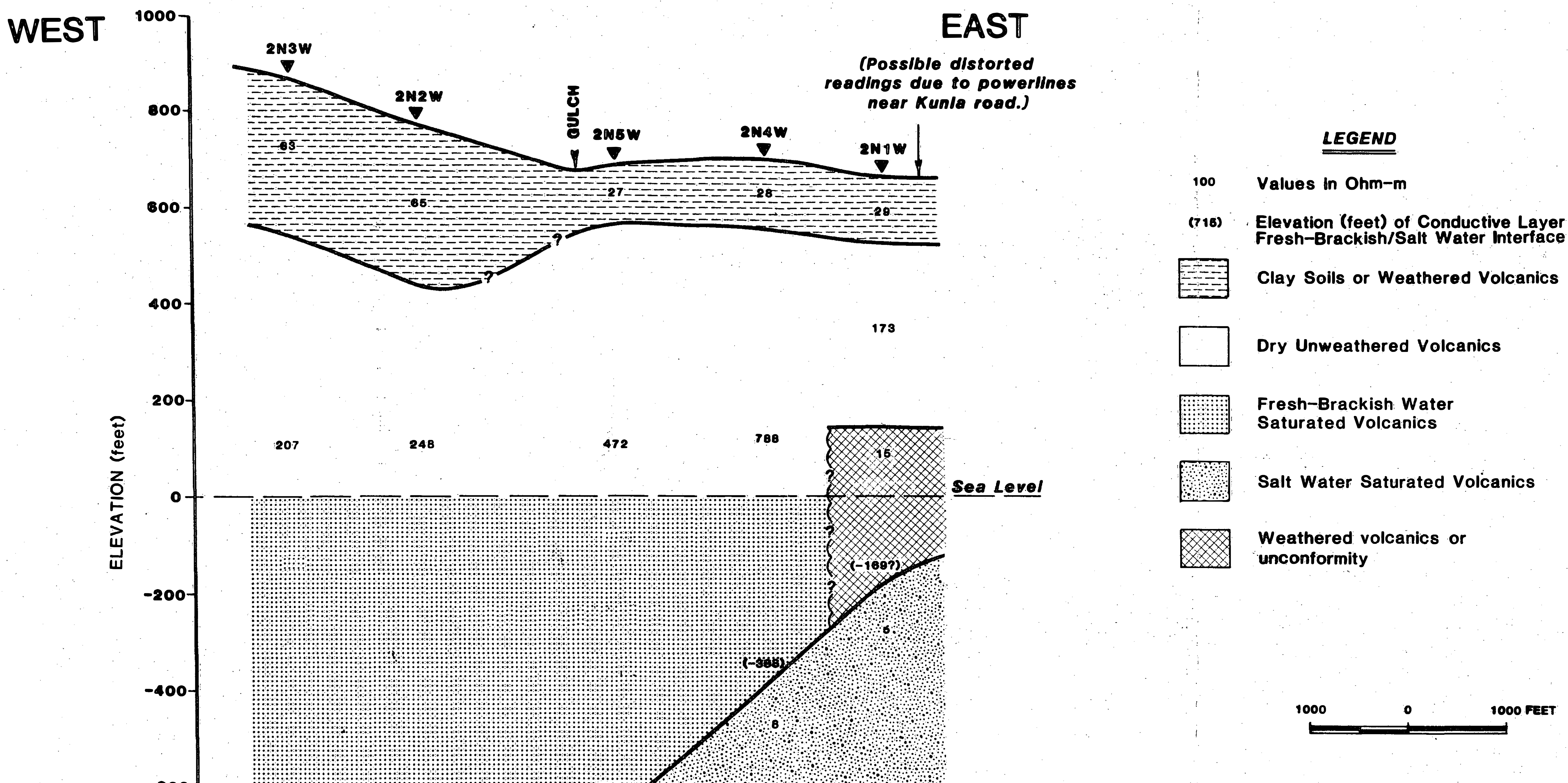
Depth (ft)	Geologic Log of Upper Honouliuli Well #2303-01 (elev. 400 ft) (static head = 17 ft)
0-50	Red clay, loose cindery red mud
50-225	Mixture of Pahoehoe and aa fresh dark grey aa, with large cuttings of dense Pahoehoe
225-379	Increased weathering, med grey Pahoehoe mixture of reddish-brown and grey aa
379-485	Red mud and compacted clay (379-415') unconformity from geologic log
485-TD	Mixture of reddish aa dark grey aa, grey Pahoehoe
TD 625'	

BLACKHAWK GEOSCIENCES, INC.

COMPARISON OF SOUNDING 1N1E AND GEOLOGIC LOG WELL 2303-01

Ewa Plains Water Dev. Corp.
Central Oahu, HI

PROJECT NO: 90034 **FIGURE 4-4**

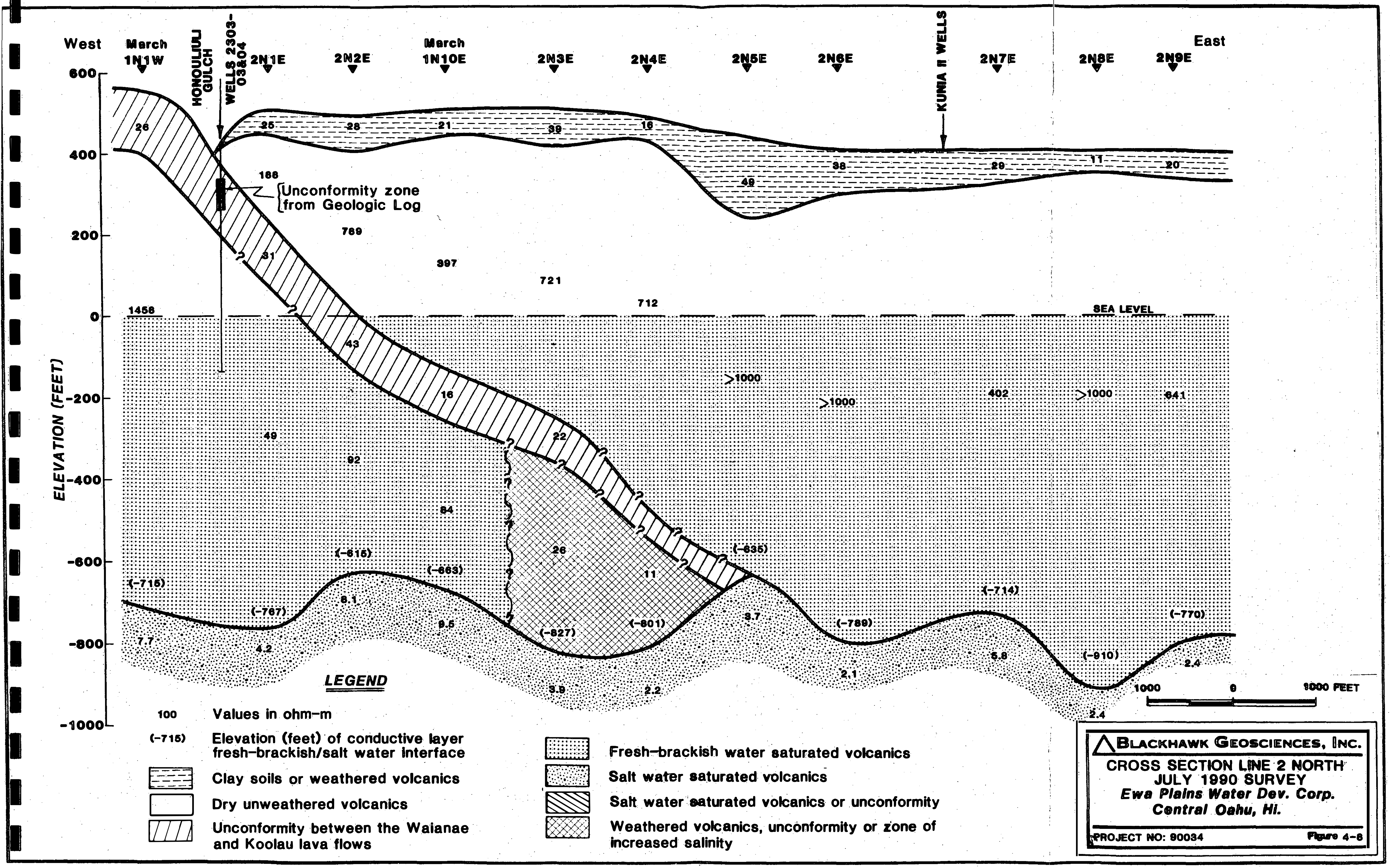


BLACKHAWK GEOSCIENCES, INC.

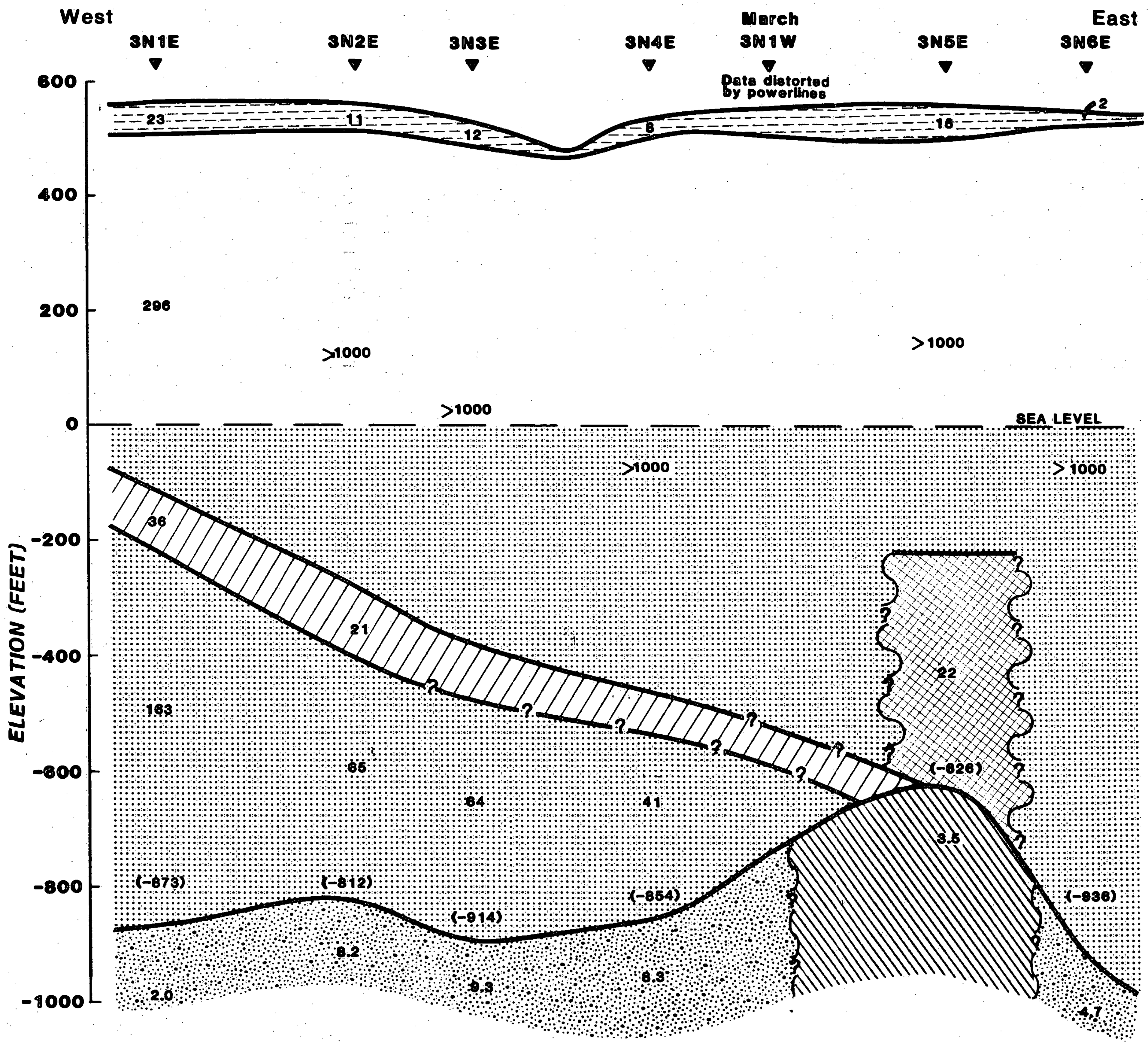
CROSS SECTION LINE 2 NORTH
MARCH 1990 SURVEY

Ewa Plains Water Dev. Corp.
Central Oahu, HI.

PROJECT NO: 90034 Figure 4-5



West
East
March 1N1W
HONOULIULI GULCH
WELLS 2303-03&04
2N1E
2N2E
March 1N10E
2N3E
2N4E
2N5E
2N6E
KUNIA II WELLS
2N7E
2N8E
2N9E
ELEVATION (FEET)
600
400
200
0
-200
-400
-600
-800
-1000
SEA LEVEL
Unconformity zone from Geologic Log
26
25
28
21
39
16
38
29
11
20
49
186
789
397
721
712
1456
31
43
16
22
>1000
>1000
402
>1000
641
49
92
84
26
11
(-615)
(-663)
(-635)
(-715)
(-767)
(-714)
(-770)
(-827)
(-801)
(-789)
(-910)
6.1
9.5
3.7
7.7
4.2
5.6
2.4
3.9
2.2
2.1
2.4
1000
0
1000 FEET
LEGEND
100 Values in ohm-m
(-715) Elevation (feet) of conductive layer fresh-brackish/salt water interface
Clay soils or weathered volcanics
Dry unweathered volcanics
Unconformity between the Waianae and Koolau lava flows
Fresh-brackish water saturated volcanics
Salt water saturated volcanics
Salt water saturated volcanics or unconformity
Weathered volcanics, unconformity or zone of increased salinity
BLACKHAWK GEOSCIENCES, INC.
CROSS SECTION LINE 2 NORTH
JULY 1990 SURVEY
Ewa Plains Water Dev. Corp.
Central Oahu, HI.
PROJECT NO: 90034
Figure 4-8



LEGEND

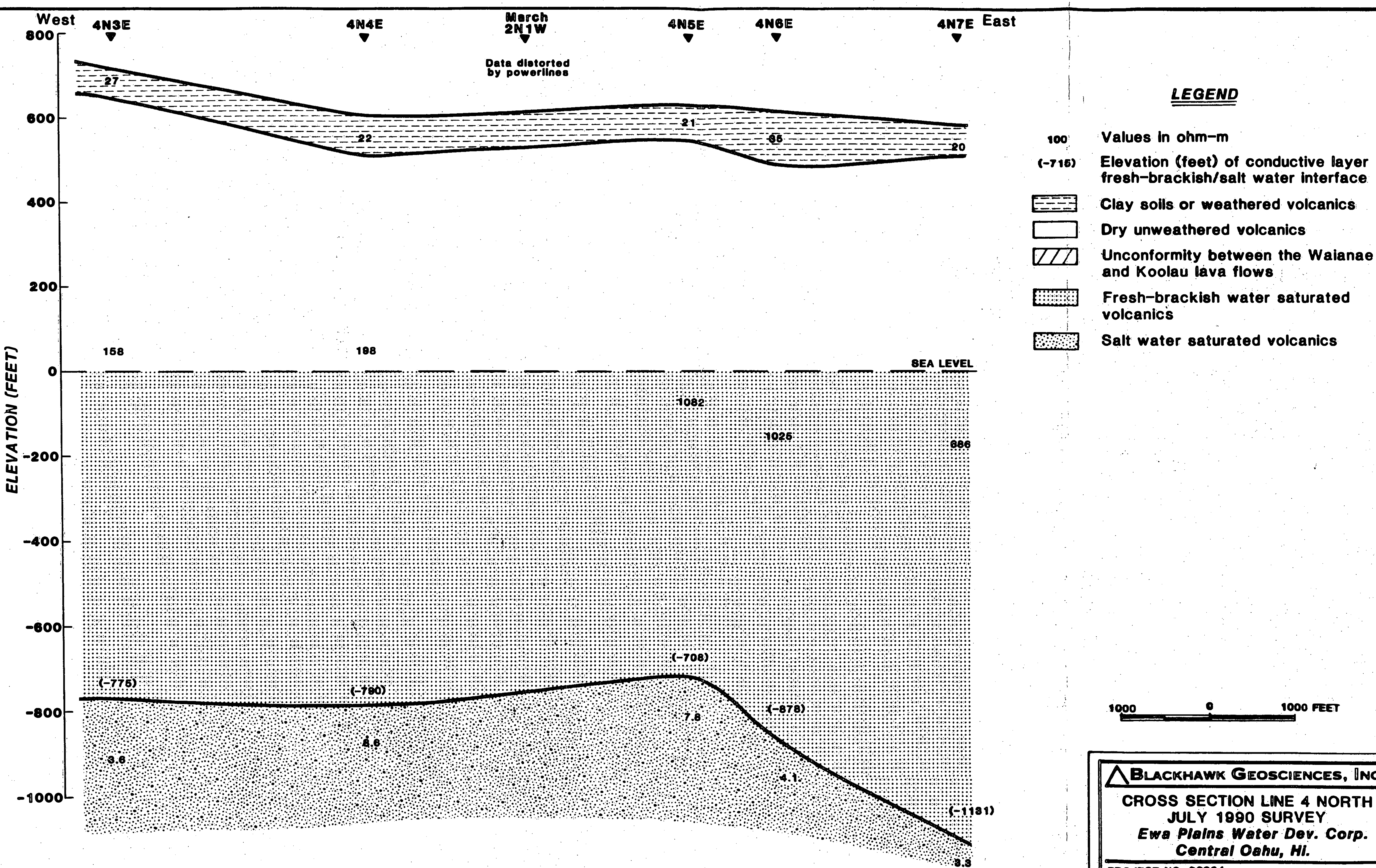
100	Values in ohm-m
(-715)	Elevation of conductive layer Fresh-brackish/salt water interface
	Clay soils or weathered volcanics
	Dry unweathered volcanics
	Unconformity between the Waianae and Koolau lava flows
	Fresh-brackish water saturated volcanics
	Salt water saturated volcanics
	Salt water saturated volcanics or unconformity
	Weathered volcanics, or zone of increased salinity

1000 0 1000 FEET

BLACKHAWK GEOSCIENCES, INC.

CROSS SECTION LINE 3 NORTH
JULY 1990 SURVEY
Ewa Plains Water Dev. Corp.
Central Oahu, Hi.

PROJECT NO: 90034 Figure 4-7

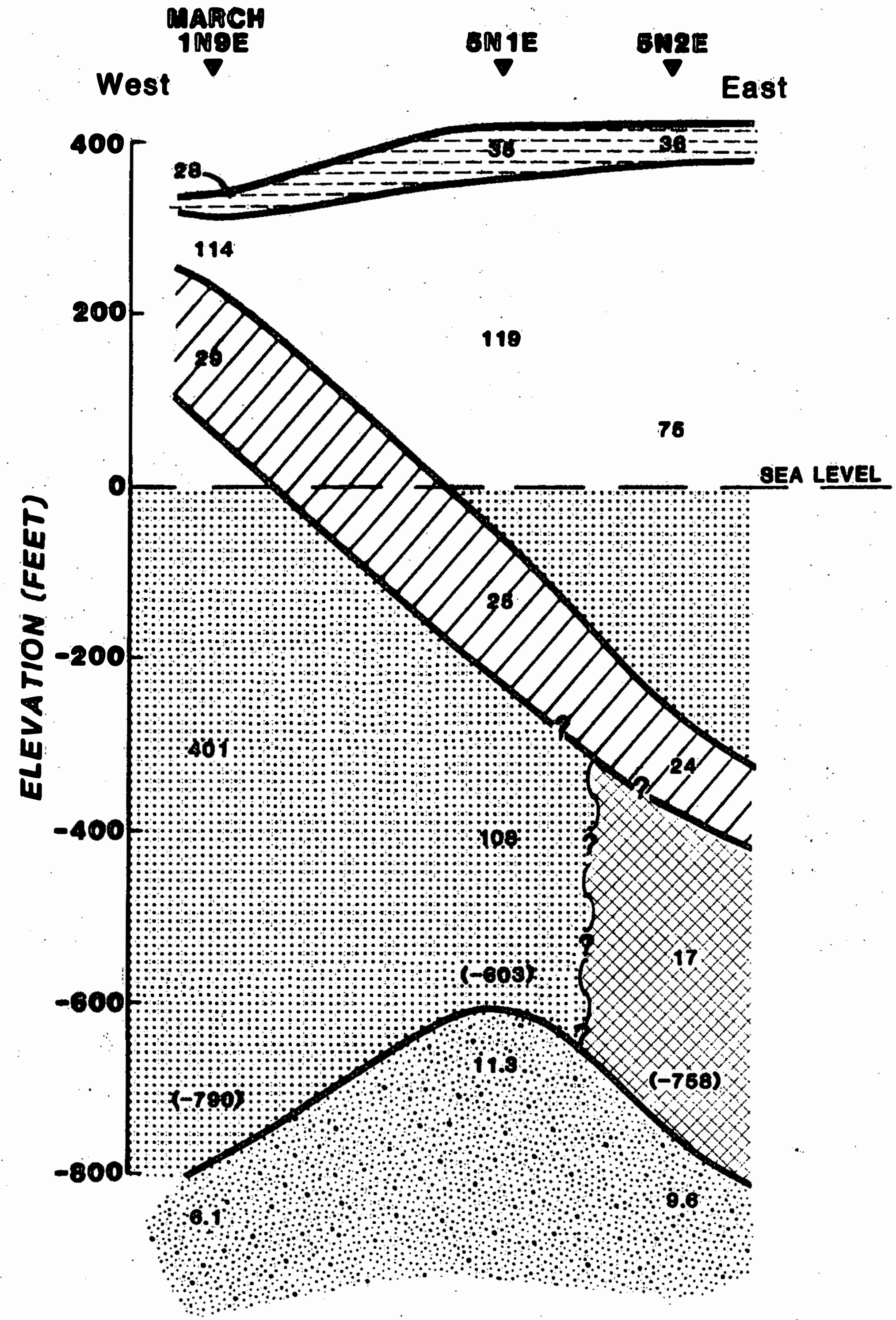


BLACKHAWK GEOSCIENCES, INC.

CROSS SECTION LINE 4 NORTH
JULY 1990 SURVEY
Ewa Plains Water Dev. Corp.
Central Oahu, HI.

PROJECT NO: 90034

Figure 4-8



LEGEND

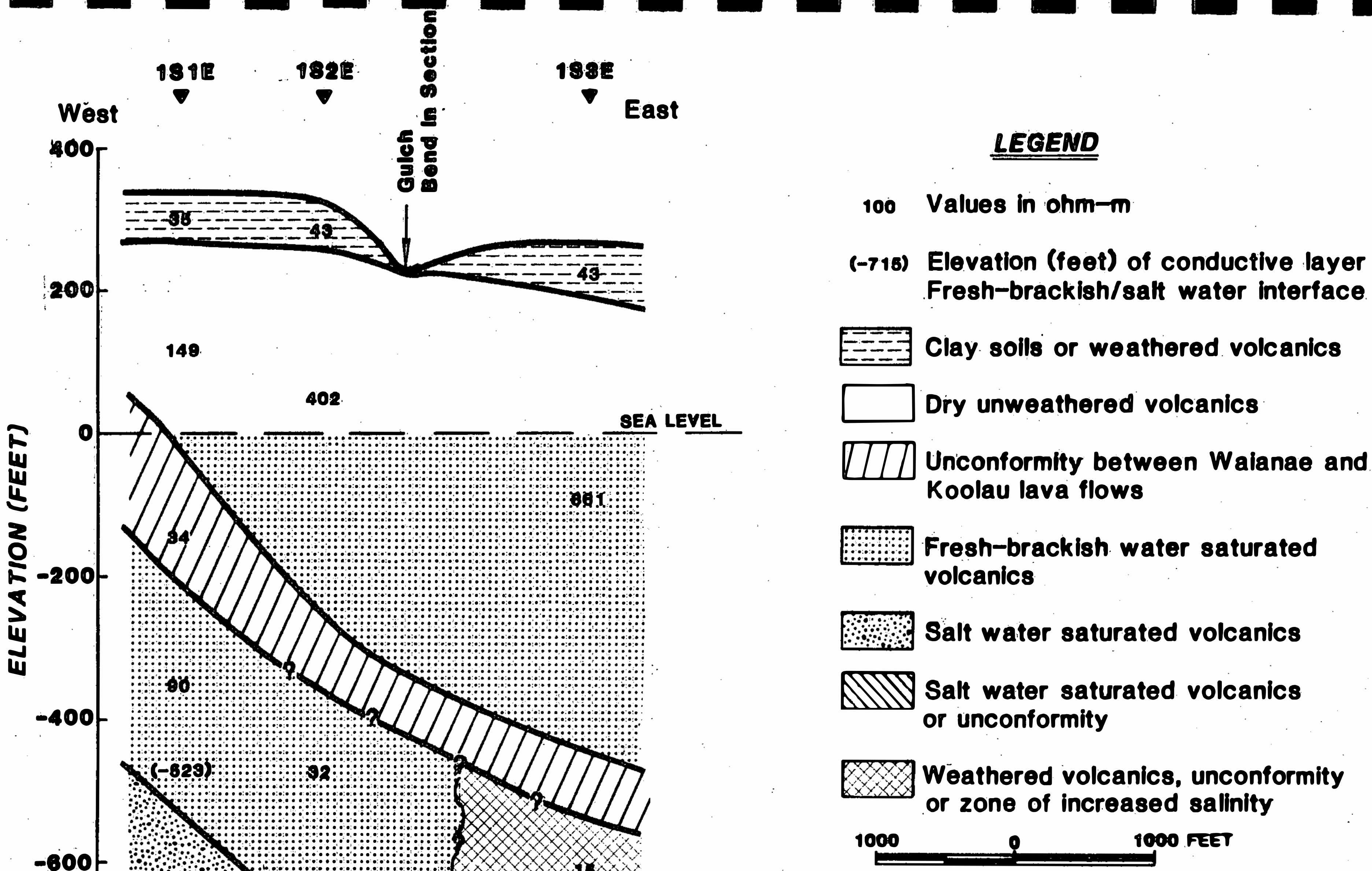
100	Values in ohm-m
(-716)	Elevation (feet) of conductive layer Fresh-brackish/salt water interface
	Clay soils or weathered volcanics
	Dry unweathered volcanics
	Unconformity between the Waianae and Koolau lava flows
	Fresh-brackish water saturated volcanics
	Salt water saturated volcanics
	Salt water saturarted volcanics or unconformity
	Weathered volcanics, unconformity or zone of increased salinity

1000 0 1000 FEET

BLACKHAWK GEOSCIENCES, INC.

CROSS SECTION LINE 5 NORTH
JULY 1990 SURVEY
Ewa Plains Water Dev. Corp.
Central Oahu, Hi.

PROJECT NO: 90040 Figure 4-9



BLACKHAWK GEOSCIENCES, INC.

CROSS SECTION LINE 1 SOUTH
JULY 1990 SURVEY
Ewa Plains Water Dev. Corp.
Central Oahu, HI.

PROJECT NO: 90034 **Figure 4-10**

5.0 CONCLUSIONS AND RECOMMENDATIONS

The objectives of the TDEM survey were to attempt to map the continuity of the unconformity between the Waianae and Koolau lava flows and to determine the elevation of the fresh-brackish/salt water interface.

5.1 UNCONFORMITY

In the Central Oahu area the TDEM soundings taken near upper Honouliuli Well #2303-01 at the 400 ft elevation (Figs. 4-3 and 4-4) show good agreement about the presence, thickness and elevation of the unconformity between the Waianae and Koolau lava flows mapped in a borehole and derived from interpretation of TDEM soundings.

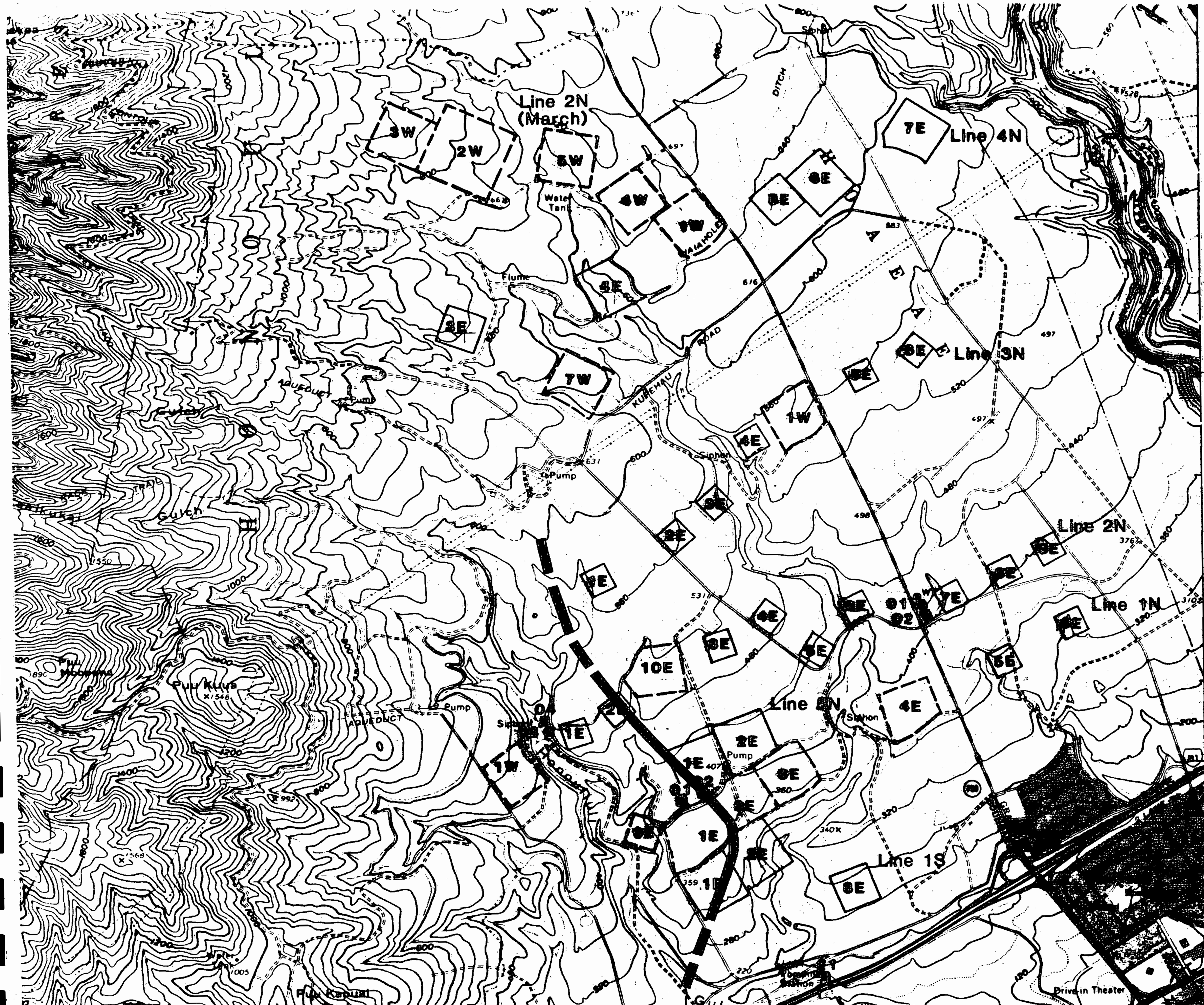
The correlation between borehole geologic log and geoelectric section was subsequently extrapolated to other lines to derive information about the presence of the unconformity. The unconformity was mapped on four lines (line 2N, July 1990; line 3N, 5N and 1S) south of line 3N, and was not detected on lines north of line 3N (lines 2N, March 1990; line 4N). The unconformity is mapped as dipping about 10^{o} towards the east, and the intersection of the unconformity at sea level was placed on a map (Fig. 5-1). The intersection of the unconformity at sea level is expected to strike northwesterly, north of line 1N and to change in a southwesterly direction south of this line. The ability to detect the unconformity deteriorated with depth and with proximity to the salt water interface.

5.2 ELEVATION OF THE SALT WATER INTERFACE

An important reason for attempting to delineate the unconformity between Waianae and Koolau lava flows is its potential influence on fresh water head. That influence can approximately be evaluated on lines 1N, 5N and 2N where TDEM measurements were made on both sides of the intersection of the unconformity with sea level. The elevations of the fresh-brackish/salt water interface derived from TDEM soundings, and the head calculated from that data using the Ghyben-Herzberg relation, show no consistent trend in head caused by the unconformity.

The TDEM results indicate that the elevations of the salt water interface are generally between -600 ft and -900 ft below msl throughout the study area, which calculates to 15 ft to 22.5 ft of head using the Ghyben-Herzberg relation. The heads observed in wells in the Honouliuli Gulch were around 17 ft and heads measured in the Kunia II well area on the central part of the study area were between 22 ft and 25 ft. Generally, the station density of wells and TDEM measurements do not justify contouring fresh water heads, or elevations of the salt water interface.

The accuracy of the TDEM survey in determining the top to the salt water interface has previously been evaluated to be ± 5% of the total depth measured. In TDEM soundings, where the unconformity is detected at or near sea level, the accuracy may be ± 10% of the total depth measured.



LEGEND

1W Sounding Loop Location

1W March 1990 Survey

01 Well Locations and Number (2303-01)

Location of unconformity at sea level dashed where approximate

OAHU

HAWAIIAN ISLANDS

QUADRANGLE LOCATION

2000 0 2000

SCALE - FEET

BLACKHAWK GEOSCIENCES, INC.

GEOPHYSICAL SURVEY INTERPRETATION MAP

Ewa Plains Water Dev. Corp.

Central Oahu, Hi.

PROJECT NO: 90034

Figure 5-1

PRINCIPLES OF TIME DOMAIN EM

BLACKHAWK GEOSCIENCES, INC.

Question.-- What is TDEM?

Answer.-- TDEM is a surface geophysical method for determining the lateral and vertical resistivity variation (geoelectric section) in the subsurface.

Question.-- What useful information can be derived from the geoelectric section?

Answer.-- Electrical resistivity can be used as an indicator for mapping several important objectives in the subsurface, such as:

1. Presence of contaminants. Dissolved solids in ground water decrease formation resistivities, so that industrial contaminant plumes and differences in salinity (e.g., salt water intrusion) can often be delineated from geoelectric sections.

2. Soil and rock types. Clays and clay shales, and formations of low hydraulic permeability, have lower resistivities than formations of high hydraulic permeability, such as sands and gravels, sandstones, basalts, and high porosity limestones. The geoelectric section can, therefore, be used to map continuity of clay and clay shale lenses.

3. Fractures and shear zones. Such zones are conduits for ground water flow and contaminant migration, and they are often characterized by zones of low resistivity. The reasons for the lower resistivities of these zones are infilling of the fracture zones by clay gouge, alteration of wall rock, and higher water contents.

Question.-- What advantages does TDEM have over other electrical and electromagnetic methods, such as resistivity (direct current) and electromagnetic conductivity profiling with the Geonics EM-31 and EM-34?

Answer.-- The advantages of TDEM over other electrical and electromagnetic methods are

- better vertical and lateral resolution
- lower sensitivity to geologic noise (see page 5)
- the ability to explore below highly conductive layers (e.g., brine saturated layers and clay lenses).

Some of the most frequently asked questions about TDEM and their answers are given below.

Question.-- Are the principles of TDEM similar to electromagnetic induction profiling, such as used in the Geonics EM-31 and EM-34?

Answer.-- Yes, the principles of electromagnetic induction profiling in the frequency domain (FDEM), used in the Geonics EM-31 and EM-34, are in many ways similar to the principles of TDEM.

An important difference between FDEM and TDEM is the current waveform driven through the transmitter loops. It is a continuous, harmonic-varying current in FDEM, and a half-duty cycle waveform in TDEM.

Question.-- Why does the current waveform of the transmitter make a large difference?

Answer.-- The large difference results from the fact that in FDEM the secondary magnetic field due to ground currents is measured when the transmitter current is on, and in TDEM when the transmitter current is off. In both cases the time-variant current driven through the transmitter causes a time-variant primary magnetic field. Associated with this primary magnetic field is an induced electromotive force (emf) that causes eddy current flow in the subsurface. The intensity of these currents is used to determine subsurface conductivities. The induced emf is a harmonic-varying function in FDEM and consists of narrow pulses in TDEM.

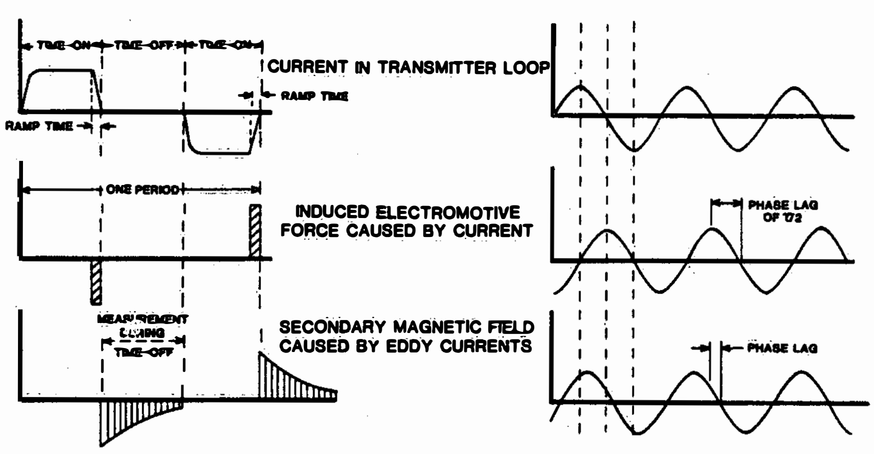


Fig. 1. System waveforms in time domain EM (TDEM) and frequency domain EM (FDEM).

The receiver measures the emf due to the secondary magnetic field of these eddy currents induced in the subsurface, and in the case of FDEM, the emf measured by the receiver is the sum of (1) the primary magnetic field (emf_p due to currents in the transmitter), and (2) the secondary magnetic field (emf_s due to eddy current flow in the ground). Thus,

$$emf_t = emf_p + emf_s$$

where subscript t, p and s refer to total, primary, and secondary magnetic field, respectively. Clearly, emf_s is the only component containing information about the subsurface. Unfortunately, in most situations, the amplitude of emf_s is only one part in 10^4 parts of emf_p. Thus, in FDEM, a small component of emf containing all the useful information about the subsurface must be measured in the presence of a large component containing no information.

In the EM-31 and EM-34 ground conductivity is determined by measuring only the component of emf_s that is in quadrature phase (90° out-of-phase) with emf_p. Unfortunately, theory shows that the in-phase component is more sensitive to ground conductivity. Measuring only the quadrature phase component limits the accuracy, exploration depth, and utility of FDEM systems.

TDEM improves the situation, because measurements are made during the time the transmitter is off. During off-time the only component of emf measured by the receiver is emf_s. Emf_s is determined in the absence of emf_p, greatly improving its accuracy of measurements.

Question.-- Briefly explain how subsurface resistivities are derived from TDEM measurements.

Answer.-- A TDEM system consists of a transmitter and a receiver. The transmitter configuration often used in ground water and environmental applications is a square loop of insulated wire laid on the ground surface (Figure 2). A multi-turn air coil receiver (about 1 m diam) is placed in the center of the loop. The sizes of the transmitter loops employed are mainly dependent upon the required exploration depth and geoelectric section. Typically, the side of a square is about one-half to two-thirds of the required exploration depth. Thus, for exploration depths to about 200 ft, 75 ft by 75 ft transmitter loops may be employed.

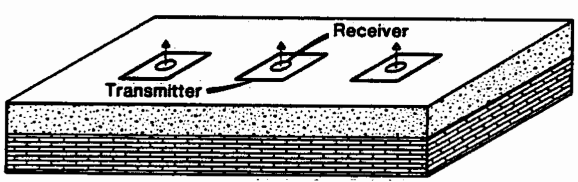


Fig. 2. Transmitter-receiver array in TDEM.

The current waveform driven through the transmitter loops is shown in Figure 1. The waveform consists of equal periods of time-on and time-off. The base frequencies employed in the Geonics instrumentation we employ can be varied from 300 hz, 30 hz, 3 hz and 0.3 hz. These frequencies result in on/off intervals of 0.833, 8.33, 83.3 and 833 msec, respectively.

The current driven through the transmitter loops creates a primary magnetic field. During the rapid current turn-off this primary magnetic field is time-variant and in accordance with Faraday's Law there will be an electromagnetic induction during this time (Figure 1b). This electromagnetic induction in turn results in eddy current flow in the subsurface. The intensity of these currents at a certain time and depth depends on ground conductivity.

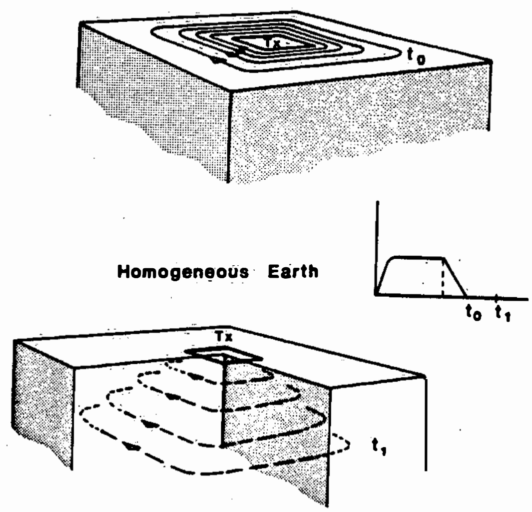


Fig. 3. Current distribution in FDEM at two times after current turn-off.

In near horizontally layered ground, the eddy currents are horizontal closed rings concentric about the center of the transmitter loop. A schematic illustration of these currents is shown in Figure 3. Immediately after turn-off (t_0) the currents are concentrated near the surface, and with increasing time currents are induced at greater depth (t_1).

The receiver measures the emf due the secondary magnetic field caused by these ground eddy currents (Figure 1c). At early time, when the currents are mainly concentrated near the surface, the emf measured will mainly reflect the electrical resistivity of near surface layers. With increasing time, as currents are induced at greater depth, the emf measured will progressively be more influenced by properties of deeper layers. Thus, in TDEM exploration, depth is mainly a function of time of measurement after turn-off.

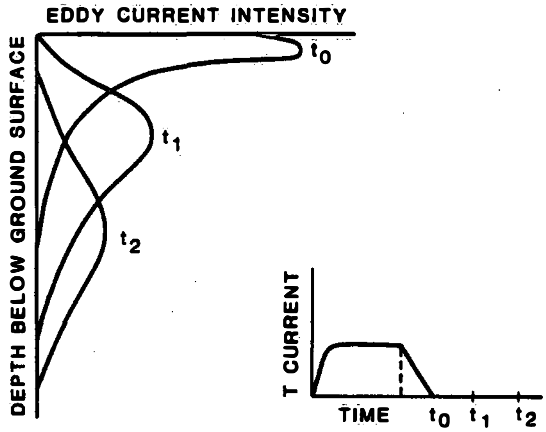


Fig. 4. Schematic illustration of eddy current distribution at different times after turn-off.

Another useful presentation of distribution of current intensity as a function of time is given in Figure 4. At early time, t_0, all currents are concentrated near the surface. At later times (e.g., t_3) the current maxima occur at increasingly greater depth. Thus, from measurements of the decay of emf at one location, the geoelectric section to a substantial depth is obtained.

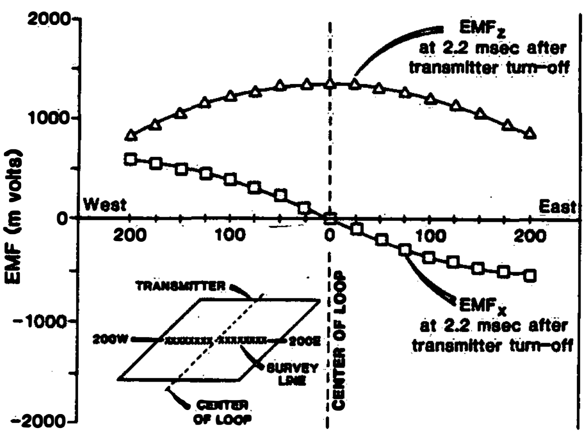


Fig. 5. Spatial behavior of emfs due to vertical (emf_z) and horizontal (emf_x) magnetic field on a profile through the center of square transmitter loop at one time (2.2 millisec) after turn-off.

The emfs caused by square transmitter loops vary with time and distance from the center. Figure 5 shows a typical measured behavior of emfs at a certain time (2.2 milliseconds) after turn-off. At other times the amplitudes will be different, but the spatial behavior is similar. The spatial behavior of the emf_z is relatively flat about the center so that measurements of emf, due to the vertical magnetic field, are relatively insensitive to errors in surveying the center of the loop, or to deviations from a square loop. This is clearly of practical value because it (1) reduces the cost of land surveys and measurement errors, and (2) allows for some flexibility in the field in positioning the measurement stations.

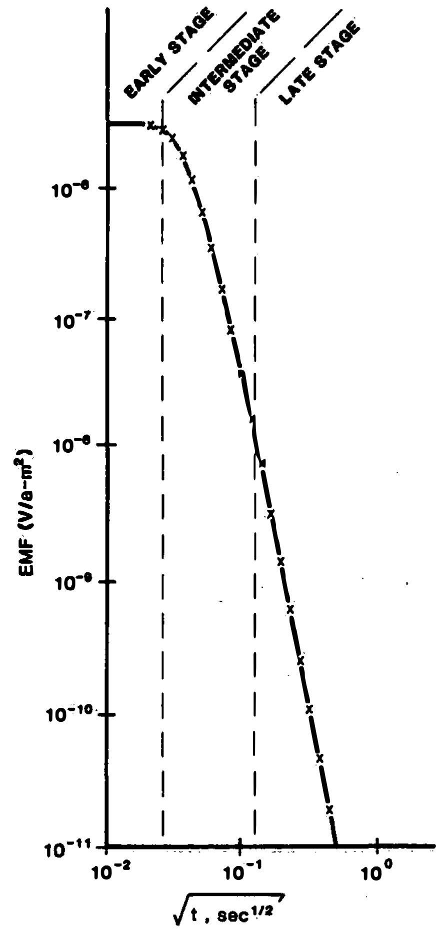


Fig. 6. Typical transient behavior of emf_z in center of square transmitter loop.

Thus, in TDEM soundings, the geoelectric section is derived from measurement of the emf due to the vertical magnetic field (emf_z) as a function of time during the period the transmitter is off. Figure 6 shows a typical behavior of emf_z as a function of time. Emf_z can be seen to decay rapidly with increasing time. One transient decay recorded over a few tens of milliseconds contains information about resistivity layering over a significant depth range.

The emfs, due to the decay of the ground eddy currents, must be measured in the presence of ambient noise sources, such as geomagnetic storms, lightning, 60 hertz powerlines, and other man-made sources. It is common to stack several hundred transient decays to improve signal to noise. Stacking of several hundred transient decays requires only a few seconds, and multiple data sets can be quickly obtained.

The processing and display of TDEM data is in many respects similar to that used in other electrical and electromagnetic methods. The objective of processing TDEM data is to obtain a solution for the resistivity stratification of the subsurface that matches the observed transient.

L022S001

MODEL: 5 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)
2.81	9.3
17.77	33.1
3.01	46.1
39.42	44.8
6.76	

TIMES	DATA LATE MEASURED	CALC LATE	% ERROR
8.90E-05	7.23E+01	7.87E+01	-8.071
1.10E-04	4.75E+01	5.11E+01	-6.997
1.40E-04	3.30E+01	3.38E+01	-2.527
1.77E-04	2.39E+01	2.45E+01	-2.280
2.20E-04	1.83E+01	1.91E+01	-4.201
2.80E-04	1.49E+01	1.55E+01	-3.952
3.55E-04	1.28E+01	1.35E+01	-5.770
4.43E-04	1.13E+01	1.22E+01	-7.412
5.64E-04	1.02E+01	1.05E+01	-3.135
7.13E-04	9.22E+00	9.31E+00	-0.981
8.85E-04	8.14E+00	8.43E+00	-3.402
1.10E-03	7.39E+00	7.52E+00	-1.740
1.41E-03	6.83E+00	6.72E+00	+1.519
1.78E-03	6.36E+00	6.36E+00	+0.002
2.21E-03	6.02E+00	6.06E+00	-0.722
2.83E-03	5.82E+00	5.86E+00	-0.728
3.57E-03	5.80E+00	5.87E+00	-1.050
4.46E-03	5.74E+00	5.82E+00	-1.432
5.67E-03	5.83E+00	5.92E+00	-1.612
7.16E-03	6.01E+00	5.98E+00	+0.543
8.81E-03	5.98E+00	6.05E+00	-1.133
1.10E-02	6.26E+00	6.17E+00	+1.339

RMS ERROR: 5.7275%

Table 1. Inversion table.

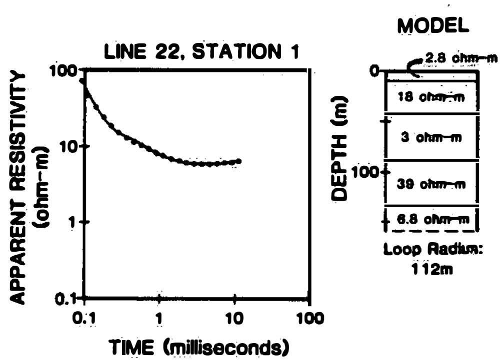


Fig. 7. Example of TDEM apparent resistivity curve and inverted geoelectric section.

The inversion of measured TDEM data into vertical resistivity stratification can be performed on a PC. An example of a data set derived for a sounding is given in Figure 7 and Table 1. In the apparent resistivity curve shown on the left (Figure 7) the measured data at each time gate is superimposed on a model curve of the geoelectric section shown on the right. This geoelectric section represents the best one-dimensional match to the experimental data. In addition to this visual display, an inversion table (Table 1) is obtained that lists (column 4) the error between measured and computed emf at each time gate, as well as an overall RMS error. The data shown on Figure 7 are typical of data quality common to TDEM soundings. Typically, 20 to 30 data points are obtained equally spaced on a logarithmic scale of time. Thus, clearly there is a major difference between TDEM soundings and profiling with the EM-31 and EM-34 (where only a few data points at different effective depths are obtained).

Question.-- If TDEM is a major improvement in electrical geophyics, why has it not been extensively used in ground water and environmental applications?

Answer.-- TDEM has been in common use in the search for base and precious metals, and for deep electrical soundings in support of hydrocarbon and geothermal exploration for about 15 years. The reason for its sparse use so far in ground water and environmental investigations was that no equipment was heretofore available for the often shallow depth (< 100 ft) requirements, common to environmental investigations.

Equipment for shallow exploration recently became available, opening a whole new range of applications for this powerful electrical measurement technique. Figure 8 shows the exploration depth range covered by various instruments.

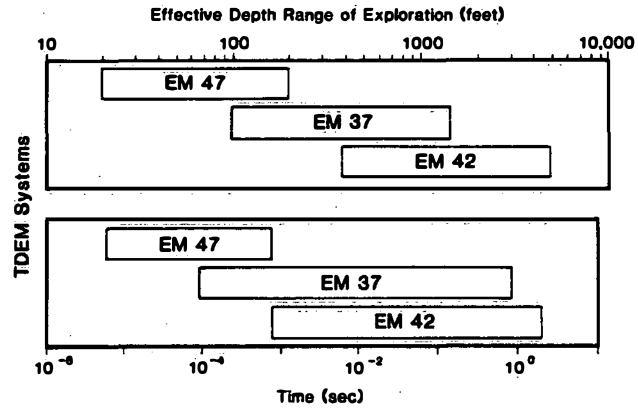


Fig. 8. Effective depth range of exploration and time range of measurement of various TDEM systems.

Question.-- What is geologic noise and why is TDEM less sensitive to such noise?

Answer.-- We define geologic noise as variation in subsurface conditions that obscures the exploration objective. Consider the schematic geologic cross section of the Floridan aquifer (Figure 9). The limestones may be overlain by overburden, likely varying laterally and vertically in soil type and thickness. At some depth in the aquifer an interface between saline and fresh water may occur, and an important exploration objective could be the mapping of this interface. Geologic noise for this objective is the change in soil type and thickness of the overburden. This noise can be very large in direct current resistivity, CSAMT and electromagnetic induction profiling.

Geologic noise is a function of the exploration objective. For example, if the objective in the setting of Figure 9 would have been the mapping of overburden thickness and type (e.g., to delineate areas of prime aquifer recharge), then what was geologic noise before becomes the exploration objective. Geologic noise is often the major cause of poor data quality in geophysical surveys for environmental and ground water applications.

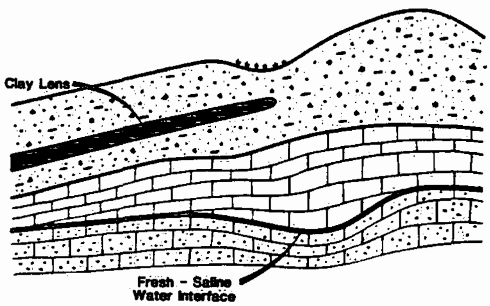


Fig. 9. Schematic geologic section of Floridan aquifer.

Question.-- How does TDEM reduce geologic noise?

Answer.-- This fact can be conceptually explained from Figure 10 where the intensity of eddy current distribution is schematically illustrated as a function of time for the FDEM and TDEM method. At early time (t_0) in TDEM all currents are concentrated near the surface, and near surface formations will largely determine the emf measured. At later time, for example, t_3, currents have largely decayed in near surface layers, and currents dominantly flow at greater depth. The emf measured at time t_3 is near transparent to near surface layers, so that their influence is greatly reduced at time t_3 and later times.

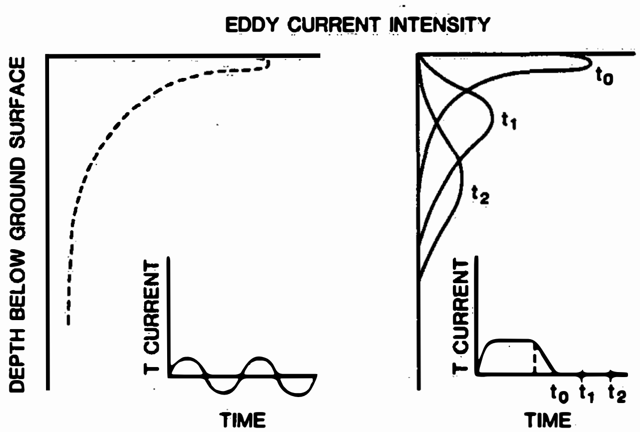


Fig. 10. Eddy current intensity in FDEM and TDEM.

In the FDEM method current intensity is always highest near the surface amplifying the influence of near surface layers.

In summary, geologic noise due to lateral and vertical resistivity variation in TDEM is reduced because:

(a) Exploration depth is mainly a function of time rather than transmitter-receiver separation. The transmitter-receiver separation need not be altered to change exploration depth as is the case in FDEM (EM-31 and EM-34), and direct current resistivity methods.

(b) Relatively small transmitter-receiver separations compared to effective exploration depth are employed.

(c) Measurements at later times are nearly transparent to near surface layers, because eddy currents at later times dominantly flow at greater depth.

Question.-- Can TDEM surveys be effective in mapping fractures and shear zones?

Answer.-- Yes, TDEM can detect contacts, fractures, and shear zones below considerable overburden thickness. The physical concepts of fracture and shear zone mapping are briefly explained.

Electrical and electromagnetic methods are often effective in mapping fractures and shear zones, because fractures and shear zones often are zones of low resistivity in more resistive host rocks. These lower resistivities are generally caused by clay gouge, higher water contents, and alteration in wall rocks. The mapping of fractures and shear zones becomes increasingly more difficult with increasing overburden thickness where outcrops are limited. It is in these situations that geophysical surveys can play an important role.

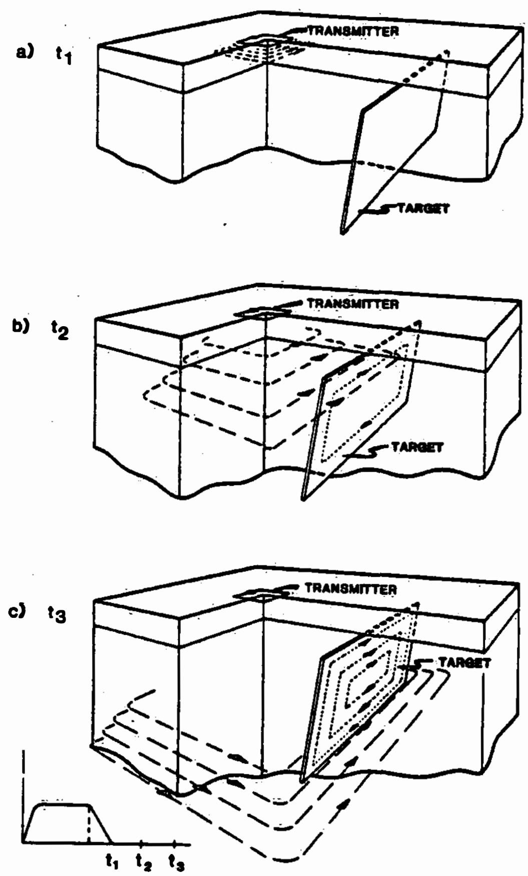


Fig. 11. Illustration of eddy current flow induced in overburden, host rock, and fracture or shear zones at different times.

Thus, in all electrical and electromagnetic methods the geoelectric section is derived by measuring resistance to current flow. We cannot selectively cause current flow in fractures and shear zones, but currents will also be induced in overburden, host rock, fractures and shear zones. The challenge is to isolate the response due to a fracture from the total response, which also contains contributions due to current flow in overburden and host rock.

TDEM is the most effective method for recognizing fractures and shear zones under overburden cover. Figure 11 conceptually explains the physical principles involved. It schematically shows a near vertical fracture zone below overburden cover, and a nearby TDEM source loop induces eddy current flow in the subsurface. At early time (t_0) eddy currents are dominantly situated in the overburden because current flow has not yet reached the fracture. Therefore, a measurement of emf at time, t_0, will not reflect the presence of a fracture zone. At later time currents are induced in the fracture, and because the fracture zone is likely less resistive than adjacent host rock, currents will be preferentially oriented in the fracture plane. In this intermediate time range the emf will contain major contributions due to currents in overburden, host rock and fractures. Currents in overburden may still dominate and fracture zones may be barely detectable. Since the fracture is less resistive than adjacent host rock, currents will decay faster in host rock than in the fracture, and there will be a time range where the fracture has maximum detectability.

To map fractures and shear zones, often different modes of surveying are employed than for determining vertical resistivity stratification (soundings). Figure 12 shows several survey modes. If the strike of the fracture is known a long transmitter loop may be laid out, and profiles are run with a receiver across the fracture zone. Also, a loop-loop array may be employed.

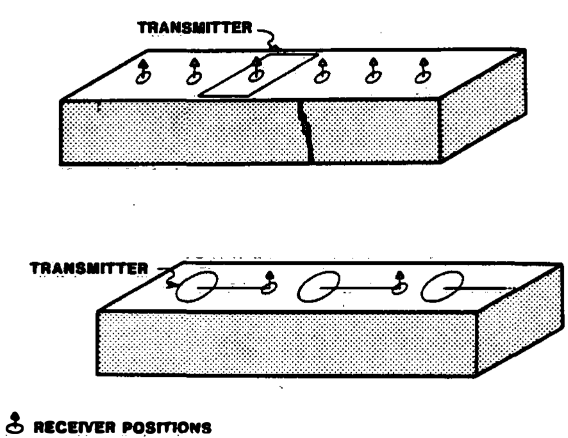


Fig. 12. Transmitter-receiver arrays useful in fracture mapping.

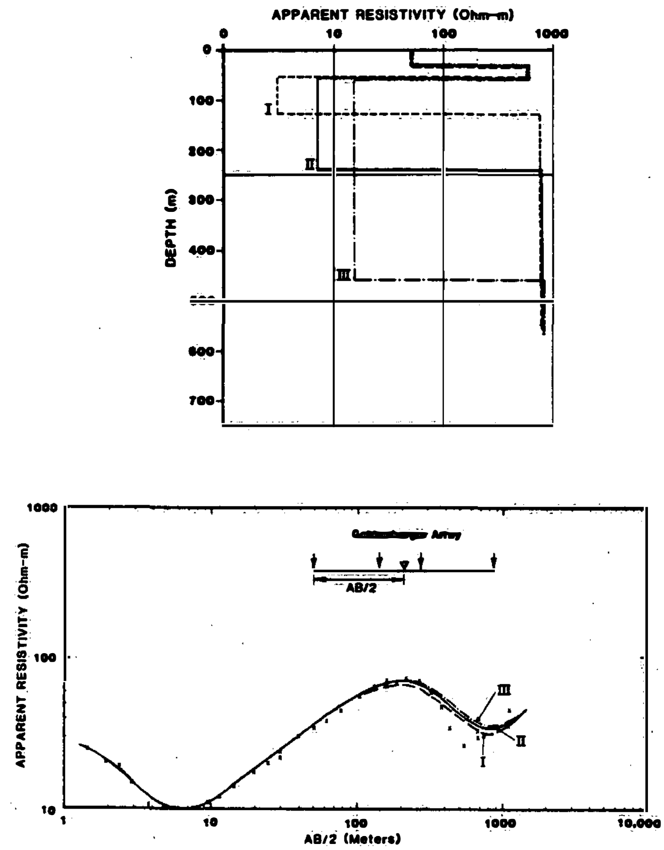


Fig. 13. Schlumberger measured apparent resistivities (a) superimposed on three one-dimensional geoelectric sections (b).

Question.-- I am from Missouri. Show me an example comparing TDEM with another electrical measurement technique next to a drill hole.

Answer.-- In a ground water survey on the coastal plain in Israel, one of the exploration objectives was to map the thickness of alluvium overlying a carbonate bedrock. A drill hole at the survey site showed depth to bedrock at about 168 m (550 ft).

The Institute of Petroleum Research and Geophysics, prior to the arrival of our TDEM crew, conducted a Schlumberger resistivity sounding near the drill hole. The results are given in Figure 13. Measurements were made to AL/2-spacing of 2,000 m (an array length of 4,000 m). The measured apparent resistivity data are superimposed on the forward models of three geoelectric sections. The three geoelectric sections are shown on the right. Clearly, the data can be fitted to any of the three models. Yet, depth to bedrock between the three sections was varied by more than 300 m. The Institute, therefore, quickly decided that Schlumberger resistivity soundings were not a viable method, because not only was a large effort required to explore to a depth of 168 m (4,000 m of line length), but its vertical resolution was meaningless.

Measurements at the same location were made with TDEM in 200 m by 200 m transmitter loops, and the results of central-loop TDEM soundings are shown in Figure 14. Again, the measured apparent resistivity curves are superimposed on three forward model curves, and the geoelectric sections of the three model curves are shown on the right. Depth to bedrock in the models is varied by 20 m. It is evident that vertical resolution of determining depth to bedrock is now $\pm$ 10 m.

Thus, not only was the physical effort required to sound to a depth of 168 m greatly reduced - only 800 m (4 x 200 m) of wire needed to be laid out, - but the vertical resolution was greatly improved.

Question.-- Summarize for me the potential of TDEM in environmental and ground water geophysics.

Answer.--Electrical surface geophysical methods are an important tool because (1) electrical resistivity is the only readily measureable physical property highly dependent of concentration of dissolved solids (water quality), and (2) electrical resistivity often closely relates to clay content and hydraulic permeability. In the past the vertical and lateral resolution of electrical methods was poor. TDEM techniques are changing that reputation.

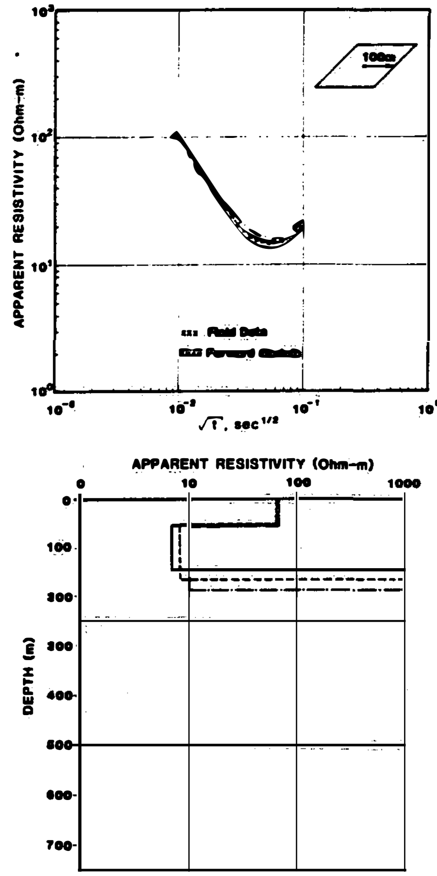


Fig. 14. TDEM measured apparent resistivities (a) superimposed on three one-dimensional geoelectric sections.

Main Office:

BLACKHAWK GEOSCIENCES, INC.
17301 WEST COLFAX AVE., SUITE 170
GOLDEN, CO 80401
(303) 278-8700
FAX (303) 278-0789

Branch Office:

BLACKHAWK GEOSCIENCES, INC.
10111 M.L. KING JR. HWY, SUITE 200-D
BOWIE, MD 20720
(301) 577-7085
FAX (301) 577-7191